

# Quark-Hadron Duality in Electron Scattering<sup>1</sup>

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**Abstract.** Quark-hadron duality addresses some of the most fundamental issues in strong interaction physics, in particular the nature of the transition from the perturbative to non-perturbative regions of QCD. I summarize recent developments in quark-hadron duality in lepton-hadron scattering, and outline how duality can be studied at future high-luminosity facilities such as Jefferson Lab at 12 GeV or an electron-hadron collider such as EPIC.

## I INTRODUCTION

Understanding the structure and interaction of hadrons in terms of the quark and gluon degrees of freedom of QCD is the greatest unsolved problem of the Standard Model of nuclear and particle physics. If one accepts QCD as the correct theory of the strong interactions, then the transition from quark-gluon to hadron degrees of freedom should in principle amount to a change of basis, with all physical quantities independent of which basis is used. However, although the duality between quark and hadron descriptions is formally exact, in practice the necessity of truncating any Fock state expansion means that the extent to which duality holds reflects the validity of the truncations under different kinematical conditions and in different physical processes. Quark-hadron duality is therefore an expression of the relationship between confinement and asymptotic freedom, and is intimately related to the nature of the transition from non-perturbative to perturbative QCD.

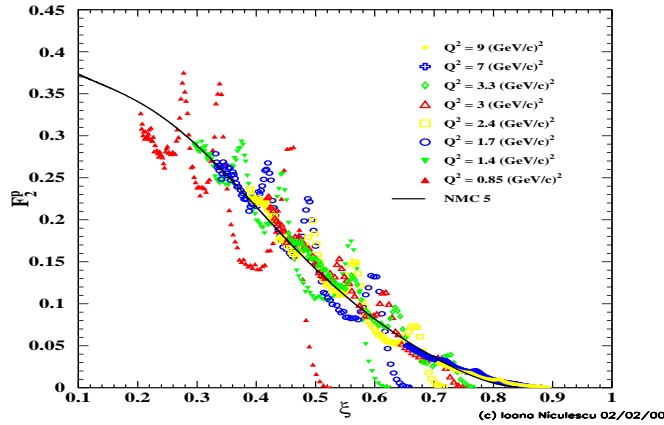
In nature, the phenomenon of duality is in fact quite general and can be studied in a variety of processes, such as  $e^+e^- \rightarrow$  hadrons, or heavy quark decays [1]. One of the more intriguing examples, initially observed some 30 years ago, is in inclusive inelastic electron-nucleon scattering.

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## II BLOOM-GILMAN DUALITY

In studying inelastic electron scattering in the resonance region and the onset of scaling behavior, Bloom and Gilman [2] found that the inclusive  $F_2$  structure function at low  $W$  generally follows a global scaling curve which describes high  $W$  data, to which the resonance structure function averages. More recently, high precision data on the  $F_2$  structure function from Jefferson Lab [3], shown in Fig. 1, have confirmed the earlier observations, demonstrating that duality works remarkably well for each of the low-lying resonances, including the elastic, to rather low values of  $Q^2$  ( $\sim 0.5 \text{ GeV}^2$ ).



**FIGURE 1.** Proton  $F_2$  structure function in the resonance region (data from a compilation [3] of JLab and SLAC data); solid line is a fit to large- $W$  deep-inelastic data at  $Q^2 = 5 \text{ GeV}^2$ .

Before the advent of QCD, Bloom-Gilman duality was initially interpreted in the context of finite-energy sum rules [4]. Formulated originally for hadron-hadron scattering, they relate the high-energy behavior of amplitudes, described within Regge theory in terms of  $t$ -channel Regge pole exchanges, to the behavior at low energy, which can be well described by a sum over a few  $s$ -channel resonances [5]. Later Harari [6] suggested a generalization of the duality picture to include both resonant and non-resonant background contributions to cross sections, in which resonances were dual to non-diffractive Regge pole exchanges, while the non-resonant background was dual to Pomeron exchange. For electron scattering, this translates into a duality between resonances and valence quarks (whose small  $x \sim 1/s$  behavior is given in Regge theory by non-diffractive Reggeon exchanges), with the background dual to sea quarks (for which the small- $x$  behavior is determined by diffractive Pomeron exchange).

In QCD, Bloom-Gilman duality can be reformulated in the language of the operator product expansion, in which QCD moments of structure functions are organized according to powers of  $1/Q^2$  [7]. The leading terms are associated with free quark scattering, and are responsible for the scaling of the structure function, while the  $1/Q^2$  terms involve interactions between quarks and gluons and hence reflect ele-

ments of confinement dynamics. The weak  $Q^2$  dependence of the low moments of  $F_2$  is then interpreted as indicating that the non-leading,  $1/Q^2$ -suppressed, interaction terms do not play a major role even at low  $Q^2$  ( $\approx 1 \text{ GeV}^2$ ).

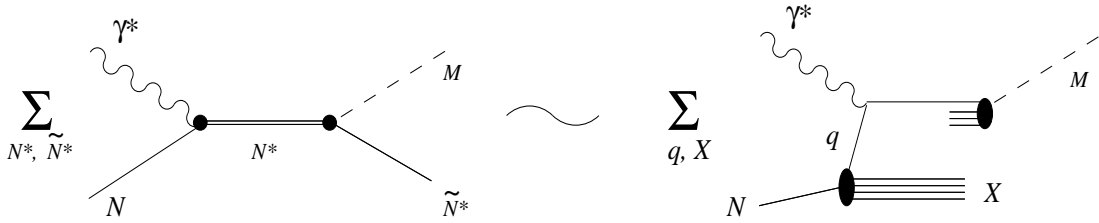
An important consequence of duality is that the strict distinction between the resonance and deep-inelastic regions is quite artificial. As observed by Ji and Unrau [8], at  $Q^2 = 1 \text{ GeV}^2$  around 70% of the total cross section comes from the resonance region,  $W < W_{\text{res}} = 2 \text{ GeV}$ , however, the resonances and the deep-inelastic continuum conspire to produce only about a 10% correction to the lowest moment of the scaling  $F_2$  structure function at the same  $Q^2$ . The deep-inelastic and resonance regions are therefore intimately related, and properly averaged resonance data can help us understand the deep-inelastic region [9,10]. This has immediate implications for global analyses of parton distribution functions, in which the standard procedure is to omit from the data base the entire resonance region below  $W = 2 \text{ GeV}$ . This is of practical relevance especially for the large- $x$  region, where deep-inelastic data are scarce [11].

### III TESTING THE BOUNDS OF DUALITY

Since the details of quark-hadron duality are process dependent, there is no reason to expect the accuracy to which it holds and the kinematic regime where it applies to be similar for different observables. In fact, there could be qualitative differences between the workings of duality in spin-dependent structure functions and spin-averaged ones [12,13], or for different hadrons — protons compared with neutrons, for instance.

At present there are data on the  $F_2$  structure function of the proton and deuteron [3], but little or no information at all exists on the spin-dependent  $g_1$  and  $g_2$  structure functions (which correspond to differences of cross sections), nor on the longitudinal to transverse structure function ratio,  $R$ . It is vital for our understanding of duality and its practical exploitation that the spin and flavor dependence of duality, as well as its nuclear dependence, be established empirically.

Another largely unexplored domain with potentially broad applications is the production of mesons ( $M$ ) in semi-inclusive electron scattering,  $eN \rightarrow e'MX$ . At high energy the scattering and production mechanisms factorize, with the cross section at leading order in QCD given by a simple product of the structure function and a quark  $\rightarrow$  meson fragmentation function, as in Fig. 2. In terms of hadronic variables the same process can be described through the excitation of nucleon resonances,  $N^*$ , and their subsequent decays into mesons and lower lying resonances,  $\widetilde{N}^*$ . The hadronic description is rather elaborate, however, as the production of a fast outgoing meson in the current fragmentation region at high energy requires non-trivial cancellations of the angular distributions from various decay channels [9,10]. Heuristically, the duality between the quark and hadron descriptions of semi-inclusive meson production (see Fig. 2) can be written as:



**FIGURE 2.** Duality between descriptions of semi-inclusive meson production in terms of quark (right) and nucleon resonance (left) degrees of freedom.

$$\sum_{N^*, \tilde{N}^*} F_{\gamma^* N \rightarrow N^*}(Q^2, W^2) \mathcal{D}_{N^* \rightarrow \tilde{N}^* M}(W^2, \tilde{W}^2) \sim \sum_q e_q^2 q(x) D_{q \rightarrow M}(z),$$

where  $D_{q \rightarrow M}$  is the quark  $\rightarrow$  meson fragmentation function for a given  $z = E_M/\nu$ ,  $F_{\gamma^* N \rightarrow N^*}$  is the  $\gamma^* N \rightarrow N^*$  transition form factor, which depends on the mass of the virtual photon and the excited nucleon ( $W = M_{N^*}$ ), and  $\mathcal{D}_{N^* \rightarrow \tilde{N}^* M}$  is a function representing the decay  $N^* \rightarrow \tilde{N}^* M$ , where  $\tilde{W}$  is the invariant mass of the final state  $\tilde{N}^*$ .

The virtue of semi-inclusive production lies in its ability to identify individual quark species in the nucleon by tagging specific mesons in the final state, enabling both the flavor and spin of quarks and antiquarks to be systematically determined. To what extent factorization applies at lower energy is an open question, and the signatures of duality in the resonance region of semi-inclusive scattering are still under investigation. Confirmation of duality in inclusive hadron production would clearly open the way to an enormously rich semi-inclusive program in the pre-asymptotic regime, allowing unprecedented spin and flavor decomposition of quark distributions.

## IV CONCLUSION

Quark-hadron duality offers the prospect of addressing the physics of the transition from the strong to weak coupling limits of QCD, where neither perturbative QCD nor effective descriptions such as chiral perturbation theory are applicable. While considerable insight into quark-hadron duality has already been gained from recent theoretical studies, it will be important in future to understand more quantitatively the features of the electron scattering data in the resonance region and the phenomenological  $N^*$  spectrum in terms of realistic models of QCD.

On the experimental side, the spin and flavor dependence of duality can be most readily accessed through semi-inclusive scattering, which requires a facility with both high luminosity and a high duty factor. Jefferson Lab at 12 GeV would be an ideal facility to study meson production in the current fragmentation region at moderate  $Q^2$ , allowing the onset of scaling to be tracked in the pre-asymptotic regime.

On the other hand, the higher center of mass energy available at an electron-hadron collider, such as EPIC, would, despite a lower luminosity, enable measurement of semi-inclusive cross sections to larger values of  $Q^2$  where perturbative QCD is more readily applicable, and factorization of the current and target fragmentation regions less problematic. Furthermore, unlike fixed-target facilities, a collider mode would allow unique access to hadrons produced in the target fragmentation region. An understanding of duality for target fragments would be the next challenge for electron scattering experiments.

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